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Sound side joint contact forces in below knee amputee gait with an ESAR prosthetic foot

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ABSTRACT

The incidence of knee and hip joint osteoarthritis in subjects with below knee amputation (BK) appears significantly higher compared to unimpaired subjects, especially in the intact side. However, it is controversial if constant higher loads on the sound side are one of the major factors for an increased osteoarthritis (OA) incidence in subjects with BK, beside other risk factors, e.g. with respect to metabolism. The aim wasto investigate joint contact forces (JCF) calculated by a musculoskeletal model in the intact side and to compare it with those of unimpaired subjects and to further elucidate in how far increased knee JCF are associated with increased frontal plane knee moments. A group of seven subjects with BK amputation and a group of ten unimpaired subjects were recruited for this study. Gait data were measured by 3D motion capture and force plates. OpenSim software was applied to calculate JCF. Maximum joint angles, ground reaction forces, and moments as well as time distance parameters were determined and compared between groups showing no significant differences, with some JCF components of knee and hip even being slightly smaller in subjects with BK compared to the reference group. This positive finding may be due to the selected ESAR foot. However, other beneficial factors may also have influenced this positive result such as the general good health status of the subjects or the thorough and proper fitting and alignment of the prosthesis.

1. Introduction

The number of subjects with amputation, especially in the lower limb, is increasing for several reasons such as rising incidence of diabetes mellitus, average age and social deprivation [1,2]. Although various prosthetic components have been designed for subjects with lower limb amputation to restore their abilities while walking, they still may have problems with their prosthesis including: Asymmetry in forces applied on the lower limbs, high energy consumption and also pain during walking [3–6]. Furthermore, subjects with unilateral BK are at risk of low back pain, knee and hip joint OA, especially in their intact limbs. Based on the results of previous studies, the incidence of knee and hip joint OA is high in intact sides of below knee amputees [7–12].

Subjects with BK typically employ compensatory mechanisms due to a lack of power generation in their ankle joint, which itself may increase the loads applied in the joints of the sound side, and due to limitations in the ankle kinematics (i.e. reduced dorsiflexion) of the prosthesis [13–16]. Sharma et al. showed that there is a correlation between magnitude of knee varus joint moment and OA symptoms based on radiologic classification [17]. Therefore, an increase in incidence of knee OA in the intact side of BK amputees may be due to an increase in applied loads. If this is the case then it should be aimed at reducing loads by proper fitting, alignment of the prosthesis and an appropriate choice of prosthetic components [18].

In the research done by Beyart et al., it was shown that the peaks of vertical components of ground reaction force (GRF) were higher in the intact limb of subjects with BK compared to the contralateral side and to normal subjects [14], respectively. Engsberg et al. also showed that subjects with BK had a greater rate of loading in their sound side [19] (eleven able bodied' children and four children with BK amputation participated in this study). In contrast, Hurley et al. showed that the forces acting across the joints of the contralateral side in adults with BK were not significantly higher than those in subjects without disability [15].

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As can be seen from the above mentioned studies, it is controversial whether the GRF of the contralateral side differ significantly from those in matched reference subjects without disability. This may be due to differing quality of prosthetic fitting, choice of prosthetic components, their alignment or any comorbidity associated with the amputation as e.g. proximal contractures and variation of the feet in the above mentioned studies. It has been shown that subjects with BK with a flex foot had a decrease in the peaks of GRF in the sound side [20].

Fey et al. showed that analyzing inter-segmental joint forces and moments did not give any reason for higher incidence of knee OA, since none of the knee kinetics parameters investigated showed higher values than in control knees. They also claimed that intact knee varus moment and force impulses in subjects with amputation were smaller than those of normal matched subjects [21]. Therefore, the high incidence of knee OA in subjects with BK may not be due to an increase in varus moment, as the results of most of the studies did not support this conclusion.

Recently there is increasing awareness, that next to joint moments it might be joint contact forces acting on the knee that may play an important role in knee osteoarthritis [23–25]. In conventional 3D-gait modeling joint loads are assessed only indirectly by monitoring joint moments [26]. However, joint loads become directly available in the context of instrumented 3D gait analysis with the use of musculoskeletal software such as Anybody (Aarlborg, Denmark) or OpenSim (Stanford University, California, USA). Therefore, and due to conflicts in the literature in this regard, it was aimed to determine specifically joint contact forces (JCF) in the intact side of subjects with BK and compare these to reference subjects to possibly find a more sensitive indicator for early OA in these subjects. We therefore specifically hypothesized in this work that a) the joint kinematics of the sound side in subjects with BK is different to age matched reference subjects leading to b) larger knee joint contact forces in this group and c) that increased joint contact forces are associated with increased coronal plane knee moments.

2. Methods

A group of seven male adults with BK all of the left leg (age: 39.4 ± 12 years, height: 1.84 ± 0.07 m) and an age and height matched group of ten reference subjects (2 female, 8 male age: 36.6 ± 12 years, height: 1.81 ± 0.07 m) without gait disability (RG) were recruited for this study. The BK group was recruited from the outpatient clinic for prosthetics as well at the in house prosthetic workshop of the Clinic for Orthopedic Surgery and Traumatology Heidelberg. The main criteria to select the subjects were non vascular induced BK amputation (e.g. trauma and tumor), use of the current prosthesis for at least 6 months, no pain or pressure sores of the residual limb, ability to ambulate independently without use of any assistive devices (e.g. crutches or canes), no proximal contracture or other neuromuscular diseases influencing their standing and walking abilities. In this study, participants with BK with a K-Level 3–4 according to Medicare Functional Classification (MFCL) were included. MFCL K-Levels were described, for instance by Gailey et al. [27]. Details on the participants with a below knee amputation can be found in Table 1.

The subjects of the RG group were healthy volunteers from the staff and students of the center. An ethical approval was obtained from the ethical committee of University Hospital. Moreover, each subject was asked to sign a consent form before data collection. It should be emphasized that all of the involved subjects who participated in this study used a Vari-Flex© foot (Ossur HF, Iceland). Otherwise, a Vari-Flex foot was fitted to their prosthesis by in-house prosthesists. The alignment of the prosthesis was adjusted based on the work of Blumentritt et al. and evaluated by using LASAR posture (Otto Bock, Duderstadt, Germany) [31]. The authors gave clear alignment recommendations for *trans*-tibial prostheses in this study, which are the following: In the sagittal plane the vertical GRF component, or the LASAR Posture laser-line should be approximately 15 mm in front of the compromise knee axis and cross the foot at one third of the foot length, measured from the heel. In the frontal plane, the vertical GRF/laser-line should be tangential to the lateral edge of the patella of the residual limb and cross the prosthetic foot through the medial aspect mimicking the big toe. All prostheses facilitated in this study were aligned according to these recommendations. Blumentritt and colleagues were able to prove that these recommendations lead to a significant decrease in knee joint coronal plane loads on the involved side [31] which were followed in this study but not documented. Based on the results of various studies, the structure of the prosthetic foot and its mechanical properties influence the gait performance of the user and also the loads applied to the body. Therefore, and in order to delete the different effects of various feet on the gait parameters of the users, it was decided that only one type of foot would be used in this study. The Vari-Flex foot was selected for this study since it can be regarded as a typical energy storing and returning (ESAR) foot. Moreover, the users were allowed to walk with the new foot for at least two weeks before data collection.

2.1. Equipment

A motion analysis system with 12 cameras (M-Cams, Vicon Motion system Limited, Oxford, UK) was used to record the motion of the subjects. The ground reaction force (GRF) was recorded by use of two Kistler force plates.

2.2. Parameters

The peak GRF in anteroposterior (gait) direction, mediolateral and vertical directions, range of motions of ankle, knee, and hip, the peak moments acting on the above mentioned joints and specifically the peak joint contact forces (JCF) in three dimensions were evaluated in this study as a possible key factor for early OA in these subjects. Moreover, the spatiotemporal gait parameters were reported in this study.

Table 1
Patient and prosthesis characteristics. Manufacturers: [1]Össur hf; Reykjavik; Iceland, [2]Blatchford Group, Basingstoke; UK, [3]Otto Bock Healthcare; Duderstadt; Germany.

ID	height [m]	mass [kg]	Age [y]	time since amputation [y]	cause of amputation	suspension method	habitual prosthetic foot
50621	187	105	48	11	tumour	Synergy Wave[1]/pin lock	Variflex[1]
52605	183	73	24.5	8	tumour	Synergy Wave[1]/pin lock	Variflex XC[1]
52644	191	89	55.9	32	bone abscess	Synergy Wave[1]/pin lock	Variflex XC[1]
53430	187	94.3	43.6	2	tumour	Synergy Wave[1]/pin lock	Flex-Foot Assure[1]
53516	183	69	23.7	4	tumour	Seal in X5[1]/valve	Reflex Shock[1]
53534	168	83	35.9	26	trauma	Synergy Wave[1]/pin lock	Variflex[1]
54003	190	95	44.2	4	trauma	Seal in X5[1]/valve	Variflex XC[1]
Mean	184.1	86.9	39.4	12.4			
SD	7.8	12.8	12.0	11.8			
Max	191.0	105.0	55.9	32.0			
Min	168.0	69.0	23.7	2.0			